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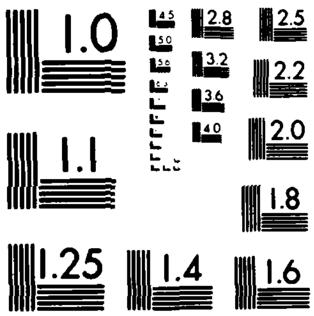

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CALCULATION OF CRITICAL TEMPERATURE FOR Nb-Cu
MULTILAYER FILM SUPERCONDUCTOR

by

Cai Xueyu and Yin Daoluo

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CALCULATION OF CRITICAL TEMPERATURE FOR Nb-Cu MULTILAYER FILM SUPERCONDUCTOR

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Received 8 July 1982

The calculation of critical temperature for Nb-Cu multilayer film superconductor without any adjustable parameter shows that as the periodic character of multilayer film is considered, the theory of proximity effect agrees reasonably with experiment within the range of layer thickness $d > 30$ Å.

It is also shown that there exists damped oscillation in the dependence of critical temperature Tcns on d, the electronic structure of interface between Nb and Cu has obvious influence upon Tcns only when $d < 30$ Å and the strong heterogeneous interface probably increases the (NV) of Nb.

For the development of preparation technique of samples, the multilayer film superconductor has attracted extensive interest. In studying the Nb-Cu multilayer film superconductor, there is special significance besides the study on ordinary multilayer film. Because the multilayer film superconductor can be considered as the presently extensively studied superconducting material, such as the simplification model of Chushi [transliteration] lines.

In 1980, Shuller et al. [1] of Argonne Laboratory made the Nb-Cu multilayer film superconductor (layered ultrathin coherent structure). Recently, they announced results of determining critical temperature T_{cns} [2]. As revealed by measurement data, the interdependent relation between T_{cns} and layer thickness d matches quite well with the proximity effect of de Gennes-

Werthamer at d>300 Å. However, when d<300 Å, the experimental data are considerably smaller than the theoretical data. Figure 1 shows the results announced by Shuller et al.

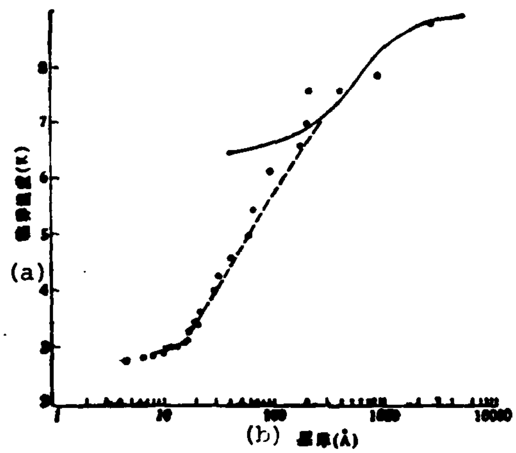

Fig. 1. Measurement results of Nb-Cu multilayer film superconductor T_{cns}: ° is the experimental data; ____ [sic] is the curve plotted according to the theory of de Gennes-Werthamer in Literature [2]; ____ [sic] is the matched curve with the experimental data in Literautre [2].
Key: (a) Critical temperature (K); (b) Layer thickness (Å).

The total thickness of Argonne sample is about 1 micron with layer thickness from 5 Å to the vicinity of 4000 Å. Therefore, the number of total layers is considerably different for different samples, from two layers to about 2000 layers. The proximity effect model of de Genner-Werthamer is only adaptable to the situation of very small number of layers. Therefore, when the number of layers is great (corresponding to the situation of very small value of d), it is necessary to sufficiently consider the

factor periodicity of the system. In Literautre [2], when applying the theory of de Gennes-Werthamer to calculate the critical temperature of the Nb-Cu multilayer film superconductor, all d is simply substituted by 1/2 d as the actual layer thickness in the original theory of de Gennes-Werthamer. Thus, the factor of periodicity is calculated. Obviously, this way of processing is oversimplified.

In the past, authors sufficiently considered the periodicity in deriving a formula of critical temperature of a multilayer film superconductor [3]. When the thickness of each layer is not too great, the energy gap function Δ can be considered as a constant in each layer. For the situation of periodicity, the following linear equations can be derived.

$$\begin{aligned} \Delta(s_1) &= (NV)_1\langle f_{11}\rangle\Delta(s_1) + (NV)_1\langle f_{12}\rangle\Delta(s_2), \\ \Delta(s_2) &= (NV)_2\langle f_{21}\rangle\Delta(s_1) + (NV)_2\langle f_{22}\rangle\Delta(s_2), \end{aligned} \tag{1}$$

In the equation, $\Delta(s_1)$ and $\Delta(s_2)$ are, respectively, the energy-gap functions of two layers; $(NV)_1$ and $(NV)_2$ are, respectively, electro-acoustic coupling coefficients of two layers; $\langle f_{ij}\rangle$ is a coefficient determined by the energy-gap equation. The critical temperature of the system can be determined by the proper-value equation of the coefficient matrix of Equations (3).

For the first approximation, in the strong heterogeneous situation (that is, considerable difference exists for (NV) of two types of metals, such as Nb-Cu), the following transcendental equation determining the critical temperature of the system can be derived:

$$\begin{aligned} \langle f_{11}\rangle &= \left(\frac{\pi k_B T}{\hbar}\right)\sum_{\omega}\frac{1}{|\omega|}(1-\lambda) = \frac{1}{NV}, \\ \lambda &= \frac{l_\omega}{\alpha d}\int_1^\infty \frac{dt}{t^3}\left\{\frac{\left[1-\exp\left(-\frac{\alpha d t}{l_\omega}\right)\right]\cdot\left[1-\exp\left(-\frac{1-\alpha}{l_\omega}dt\right)\right]}{\left[1-\exp\left(-\frac{dt}{l_\omega}\right)\right]}\right\}, \end{aligned} \tag{2}$$

In the equation, the definition of the following quantities is as follows:

κ_B and $\hbar$ are, respectively, the Boltzmann and Plank constants:

$$\omega = (2n+1)\frac{\pi k_B T}{\hbar} \qquad n = 0, \pm 1, \pm 2, \cdots;$$

$\alpha = d_1/d$; d_1 is the thickness of the superconducting layer, and d is the summation of the superconducting layer and normal-layer thickness; $l_\omega = v_F/2|\omega|$, v_F is the Fermi speed; 1/NV is the reciprocal of the electro-acoustic coupling coefficient of the superconducting layer.

Based on Eq. (2), the authors conducted numerical calculation of the non-adjustable parameter on T_{cns} of samples of Argonne multilayer film by using parameters in Literature [2]. Figure 2 shows the calculation results.

During calculation, the followign parameters published in Literature [2] are used:

Specific-heat coefficient of electrons $\gamma_{Nb} = 7.5\times10^2$ J/m^3K^2; the product of average free range of resistivity and electrons $(\rho l)_{Nb} = 1.5\times10^{-15}$ $\Omega . m^2$; $T_{c(Nb)} = 8.91$ K.

From the aforementioned parameters, all parameters required in calculation of Eq. (2) can be obtained: $\alpha = 0.5$;

$$v_{F(Nb)} = \pi^2 k_B^2/e^2 \gamma_{Nb}(\rho l)_{Nb} = 2.05 \times 10^7 \text{cm/s}^{[4]};$$

$$\frac{1}{NV} = \ln\frac{1.45 T_{c(Nb)}}{\theta_{D(Nb)}} = 3.06^{[2]},$$ θ_D is the Durban temperature, taken as 275 K.

The interruption of BCS rule is applied for summation of ω.

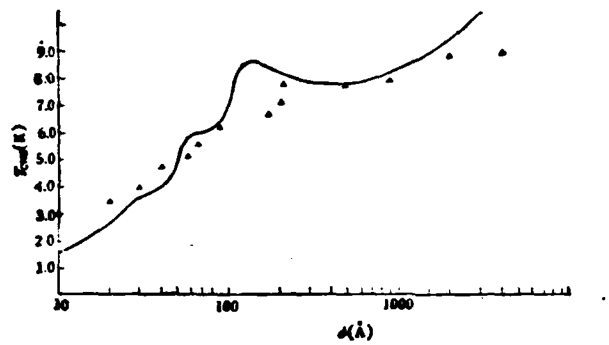

Fig. 2. Relationship T_{cns}-d given in Eq. (2): ___ is the theoretical curve; Δ is the experimental data.

We can clearly see from Fig. 2 that when d is a relatively large number (with a smaller number of layers), the de Gennes-Werthamer curve and the experimental data coincide with each other. Results calculated from Eq. (2) are relatively in the high value range. This is obviously because of the following: 1. When the value of d is relatively great without the existence of periodicity; 2. it is caused by not satisfying the condition that Δ is a constant in the derivation process of Eq. (2).

Within the range of 30 Å<d<2000 Å, Eq. (2) coincides with the experiments. Considering that without using the accuracy degree of any adjustable parameter and parameters such as γ_{Nb} and $(\rho\ell)_{Nb}$; this coincidence is satisfactory.

When d<300 Å, Eq. (2) gives the T_{cns}-d relation showing the damped oscillation attenaution, referring to Fig. 2. The experimental data clearly show this trend, referring to Fig. 1. At the value of the first peak where d∿200 Å, the experimental data are not concentrated enough; the peak value is not clear enough but displays very strong scattering characteristics. Evidence from further experiments can be easily obtained.

We still do not understand the physical regime of this damped oscillation attenuation. It is estimated that in the periodic nonhomogeneous system, it may exist the phase interference phenomenon of the macroscopic wave function.

When d is very small (<30 Å), the interface has a stronger effect on (NV) of Nb; this point has not been considered during derivation of Eq. (2). This is very possibly because of greater deviation between experimental data and results of Eq. (2) in this region. If this conclusion is established, this reveals that the interface can have a clear influence within a very small range (<30 Å). It is worthwhile to point out that the result of Eq. (2) has an intensification function on NV of Nb by comparatively explaining the strong heterogeneous interface. This is just the opposite conclusion to that in Literature [2]; further study is worthwhile.

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